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AN INTEGRATED CALIBRATION TECHNIQUE FOR STEREO VISION SYSTEMS (PREPRINT)

A.M. Vader, A. Chadda, W. Zhu, M.C. Leu, and X.F. Liu

University of Missouri-Rolla

J.B. Vance

Boeing Research and Technology

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MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
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A.M. Vader, A. Chadda, W. Zhu, M.C. Leu, and X.F. Liu (University of Missouri-Rolla)
J.B. Vance (Boeing Research and Technology)

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AN INTEGRATED CALIBRATION TECHNIQUE FOR STEREO VISION SYSTEMS

A. M. Vader
Dept. of Mechanical & Aerospace Engineering
Missouri University of Science and Technology
Rolla, MO 65409, USA
amv6w3@mst.edu

A. Chadda
Dept. of Computer Science
Missouri University of Science and Technology
Rolla, MO 65409, USA
ac5x7@mst.edu

W. Zhu
Dept. of Mechanical & Aerospace Engineering
Missouri University of Science and Technology
Rolla, MO 65409, USA
zhuwe@mst.edu

M. C. Leu
Dept. of Mechanical & Aerospace Engineering
Missouri University of Science and Technology
Rolla, MO 65409, USA
mleu@mst.edu

X. F. Liu
Dept. of Computer Science
Missouri University of Science and Technology
Rolla, MO 65409, USA
fliu@mst.edu

J. B. Vance
Boeing Research and Technology
St.Louis, MO 63105, USA
Jonathan.B.Vance@boeing.com

ABSTRACT

This paper presents the integration and evaluation of two popular camera calibration techniques for stereo vision system development for motion capture. An integrated calibration technique for stereo vision systems has been developed. To demonstrate and evaluate this calibration technique, multiple Wii Remotes (Wiimotes) from Nintendo were used to form stereo vision systems to perform 3D motion capture in real time. This integrated technique is a two-step process: it first calibrates the intrinsic parameters of each camera using Zhang's algorithm [5] and then calibrates the extrinsic parameters of the cameras together as a stereo vision system using Svoboda's algorithm [9]. Computer software has been developed for implementation of the integrated technique, and experiments carried out using this technique to perform motion capture with Wiimotes show a significant improvement in the measurement accuracy over the existing calibration techniques.

KEYWORDS: Camera calibration, Stereo vision, Wiimote, Motion capture.

1. INTRODUCTION

Systems based on mechanical, magnetic, acoustic, inertial and optical technologies for motion capture for interactive computer graphic simulation and other applications have been explored by researchers for many years and commercial products are continuously evolving. In particular, multi-camera systems have continued to evolve because of continuously decreasing prices of powerful computers and cameras. Among them infrared based optical motion capture systems (e.g. iotracker, PhaseSpace, Vicon, ART Gmbh, NaturalPoint) are becoming increasingly popular because of their higher precision and better flexibility. These systems are less susceptible to adverse shop floor conditions.

Good calibration is the key to the efficient use of a multi-camera stereo vision system. The calibration method largely depends on available resources. Kitahara et al. [1] calibrated their large-scale multi-camera environment by using a classic method [2]. The 3D points were collected by a combined use of a calibration board and a 3D laser surveying instrument. The cost of the calibration hardware required for this method is much higher than the cost of the cameras. In comparison, the calibration technique discussed in the present paper requires minimum investment in the calibration hardware and thus is ideal for cheap IR cameras like Wii Remotes (Wiimotes) used in Nintendo Wii games.

Many researchers have successfully dealt with the problem of camera calibration by taking images from a 2D object consisting of a planar pattern [3, 4, 5]. Most of the other calibration techniques using planar objects are directly or indirectly derived from these techniques. Tsai's method of camera calibration is a classic one and is still widely used in computer vision, and there have been implementations of this method in C/C++ and other programming languages. The DLT-based calibration model presented by Heikkilla and Silven [3] uses the concepts and techniques of Melen [6] in photogrammetry, and its implementation is available as a

MATLAB software package. Zhang's method [5] is a newer one and it makes use of advanced concepts in projective geometry, and the implementation of this method is also available in a MATLAB toolbox.

A detailed comparative study of the above three methods has been carried out by Zollner and Sablatnig [7], whose experimental evaluations indicated that the overall error of the DLT-based estimation is significantly smaller than Tsai's method in the mono-view case, but the DLT-based method generates larger errors than Zhang's method in the multi-view case.

We recently developed a technique to integrate multiple stereo vision systems, each consisting of 2 digital cameras, with the individual stereo vision systems calibrated with Zhang's algorithm [5] to determine the camera's intrinsic and extrinsic parameters. These individually calibrated systems are then calibrated together using Horn's algorithm [8] to determine their relative positions and orientations. The implementation of this technique showed that a single stereo system with two Wiimotes offered an accuracy of 2.7 mm, while an integrated, two-stereo system with two Wiimotes each for a total of four Wiimotes offered an accuracy of 18.9 mm.

In the present paper we develop and evaluate an integrated technique to calibrate multiple cameras together to form a low-cost motion capture system. This is a two-stage calibration technique: first the intrinsic parameters are determined with Zhang's method [5] and then the extrinsic parameters are determined with Svoboda's method [9]. Individual stereo vision systems could be further integrated using Horn's algorithm [8] to extend the range of motion capture. We have successfully implemented this integrated technique and demonstrated it with good measurement accuracy with multiple Wiimotes.

2. INDIVIDUAL AND MULTIPLE STEREO VISION SYSTEM CALIBRATION

2.1 Intrinsic and Extrinsic Parameters of a Stereo Vision System

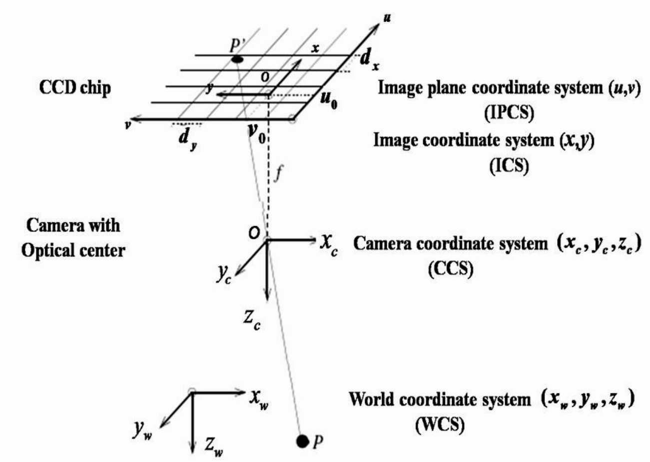

Figure 1. Pinhole camera model

In the camera calibration, the transformation between 3D world coordinates and 2D image coordinates is determined by solving the unknown parameters of the camera model. The perspective projection (i.e., pinhole) camera model is illustrated in Fig. 1. The center of projection is at the origin O of the camera coordinate system. The image coordinate system is parallel to the camera coordinate system, with a distance f (focal length) from O along the z_c axis, which is the optical axis or the principal axis. The intersection between the image plane and the optical axis is the principal point o. The u and v axes of the image plane coordinate system are parallel to the x and y axes, respectively. The coordinates of the principal point in the image plane coordinate system are (u_0, v_0).

As shown in Fig. 1, let P be an arbitrary point located on the positive side of the z_c axis and p be its projection on the image plane. The coordinates of P in the camera coordinate system are (x_c, y_c, z_c) and in the world coordinates system is (x, y, z). The coordinates of p in the image plane coordinate system are (u, v), which are related to (x, y, z) by the following equation:

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A\,[R\;\;T] \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \tag{1}$$

where

$$A = \begin{bmatrix} \alpha_x & s & u_o \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

R and T are the rotation matrix and translation vector which relate the world coordinate system to the camera coordinate system. R and T each consists of three independent parameters, which are the extrinsic parameters of each camera. A is the intrinsic parameter matrix, where the parameter s represents the skewness of the image in terms of the two image axes, α_x=f/d_x and α_y=f/d_y are scaling factors in the image u and v axes, respectively, f is the camera focal length, d_x and d_y are the pixel dimensions in the x and y directions, respectively, and λ is a scale factor. Determining the intrinsic and extrinsic parameters is essential to the calibration of a stereo vision system with digital cameras.

2.2 Establishing a Stereo Vision System with Two Cameras Using Zhang's Algorithm

To establish a stereo vision system with two cameras, the relationship between the two camera coordinate systems also needs to be calibrated. For a point P in 3D space, its two coordinates P_L and P_R in the left and right camera coordinate systems have the following relationship:

$$P_R = R_s * P_L + T_s \tag{2}$$

where R_s is the rotation matrix and T_s is the translation vector between the two coordinate frames of the stereo vision system.

To calibrate a stereo vision system using Zhang's technique [5], a calibration plate can be used. For example, Fig. 2 shows an experimental setup for collecting the calibration data for Wiimotes using a 36 LED calibration plate shown in Fig. 3. During the calibration process, the calibration plate is moved to different locations in the field of view of the Wiimotes. Readings are taken only when all the 36 LEDs on the calibration plate can be seen by both Wiimotes for a given position of the calibration plate. In Fig. 2, which has four Wiimotes mounted on a ceiling bar of a 10'x10'x10' CAVE (Computer Automated Virtual Environment), two stereo systems are formed of two Wiimotes each, from a setup of 4 Wiimotes. Figure 4 indicates a pictorial representation of the 36 LEDs at two different locations as seen by a Wiimote in the camera coordinate system. The pixel coordinates of each LED at each fixed location can be read from the Wiimote. Together with the known world coordinates of each LED's position, the intrinsic parameters of the Wiimote can be calculated using the Camera Calibration Toolbox of MATLAB, which was developed by Bouguet [10] based on Zhang's algorithm.

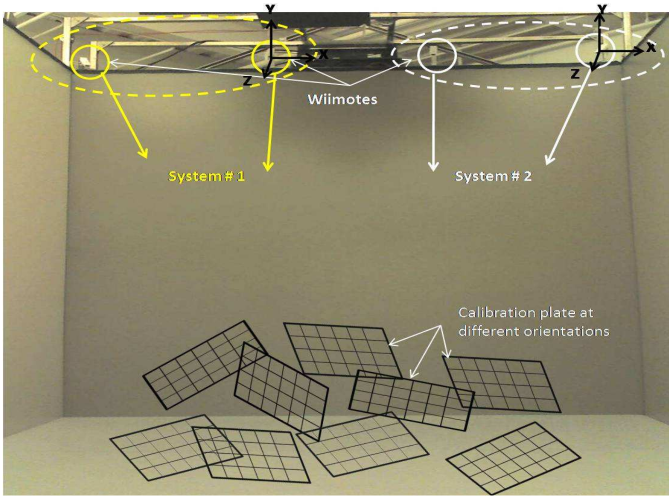

Figure 2. Calibration with Zhang's method using a calibration plate with 36 IR LEDs

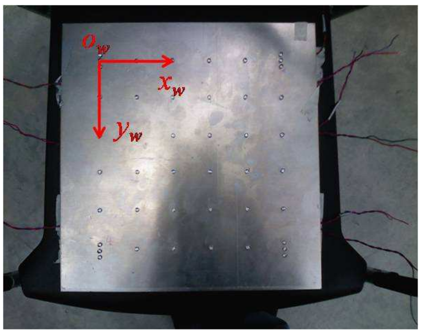

Figure 3. The calibration plate with 36 IR LEDs

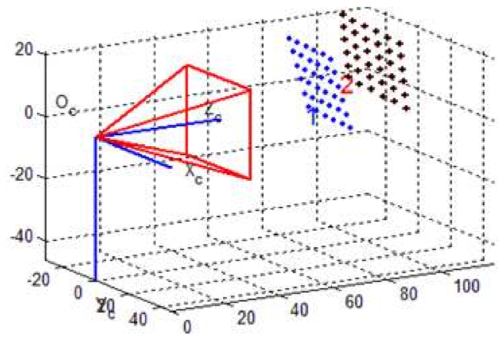

Figure 4. Data collected during the calibration

After the calibration of each camera, the calibration results from the two cameras can be used to calibrate the two-camera stereo vision system. There exists a relationship between the world coordinate system and the camera coordinate system through the extrinsic parameters, i.e., the rotation matrix R and translation vector T, as follows:

$$P_{CL} = R_1 * P_1 + T_1 , \quad P_{CR} = R_2 * P_2 + T_2 \tag{3}$$

where P_{CL} and P_{CR} represent the point's 3D coordinates in the left camera frame and in the right camera frame, respectively, P_1 and P_2 are two points expressed in the world coordinate system, R_1 and T_1 are the calibration result of extrinsic parameters for the left camera, and R_2 and T_2 are the calibration results of extrinsic parameters for the right camera. The two points P_1 and P_2 in the calibration are the same point, thus P_1=P_2. From equation (3) we have the following relationship:

$$P_{CR} = R_2 * R_1^{-1} * P_{CL} + (T_2 - R_2 R_1^{-1} T_1) \tag{4}$$

The above equation can be written in the form of

$$P_{CR} = R_S P_{CL} + T_S \tag{5}$$

where R_S is the rotation matrix and T_S is the translation vector that represent the transformation between the two camera coordinate systems.

2.3 Calibration of Multiple Stereo Vision Systems

Often two or more stereo vision systems need to be integrated into a single system in order to provide a larger coverage volume. In this case, each stereo system generates the 3D coordinates of measured points with respect to its own coordinate system. To integrate these vision systems into one single system, it is necessary to determine the relative position and orientation among the various sub-stereo-vision systems.

Consider a set of 3D points measured by two stereo vision systems, each having its local coordinate frame. These points can simply be the positions occupied by a marker, which is moved randomly in 3D space, as shown in Fig. 5, such that the

marker is seen by both stereo systems at each time the data is read.

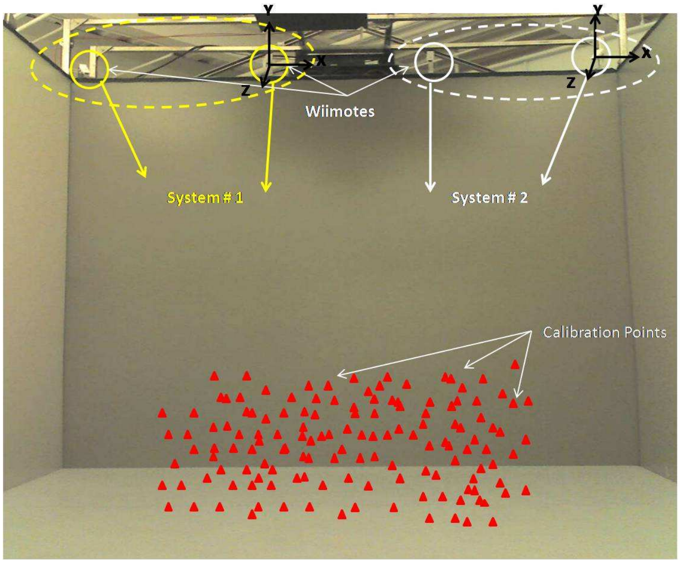

Figure 5. Integration of two stereo vision systems using Horn's algorithm

Suppose there are n different positions of the marker in 3D space. For the i^{th} position, let the data read by the left camera be represented as $r_{l,i}$ in the left camera coordinate system, and the data read by the right camera be represented as $r_{r,i}$ in the right camera coordinate system.

The centroids $\overline{r}_l$ and $\overline{r}_r$ of the two sets of data can be calculated in the left and the right coordinate systems, respectively, as follows:

$$\overline{r}_l = \frac{1}{n}\sum_{i=1}^{n}(r_{l,i}) \text{ , } \overline{r}_r = \frac{1}{n}\sum_{i=1}^{n}(r_{r,i}) \qquad (6)$$

The transformation from the left to the right coordinate system has the form

$$\overline{r_r} = sR\,(\overline{r_l}) + T_o \qquad (7)$$

where s is a scale factor, T_o is the translation, and $R(\overline{r_l})$ denotes the rotation of vector $\overline{r_l}$.

Considering the inaccuracy of the camera calibration results and the inconsistencies in the camera hardware, it is practically impossible to find a unique transformation that maps the entire set of measured coordinates of a set of points in one coordinate system exactly into the measured coordinates of these points in the other coordinate system. The residual error can be written as

$$e_i = r_{r,i} - sR\,(r_{l,i}) - T_o \qquad (8)$$

The root mean square (RMS) of errors for n data points can be calculated as

$$\sqrt{\sum_{i=1}^{n} ||e_i||^2}$$

The classical approach of finding the transformation parameters s, R and T_o is to minimize the sum of squares of errors numerically. However, Horn [8] derived a closed-form solution to the least-square problem by use of unit quaternions to represent rotation. This solution has been coded into a software routine by Wengert and Bianchi [11] and we used it to determine the transformation parameters in calibrating two stereo vision systems with respect to each other.

2.4 Evaluation Results

Figure 6 shows the measurement accuracy of a single-stereo system consisting of two Wiimotes using Zhang's algorithm. The average magnitude of measurement error is 2.7 mm. Figure 7 shows the measurement accuracy of a stereo system formed by integrating two single-stereo systems together using Horn's algorithm. The integrated system consists of a total of four Wiimotes and covers a larger measurement volume compared to a single-stereo system with two Wiimotes. However, the average magnitude of measurement error has increased to 18.9 mm.

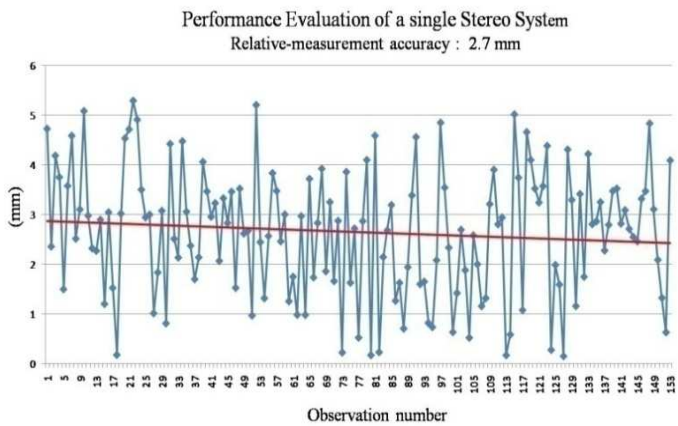

Figure 6. Measurement accuracy for a single stereo system of 2 Wiimotes

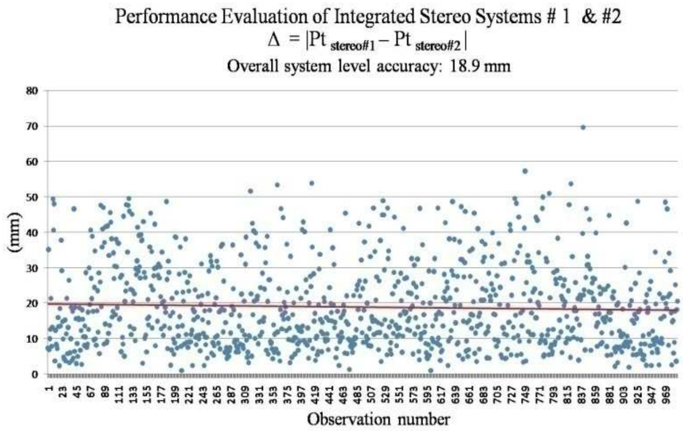

Figure 7. Measurement data with two stereo systems of 2 Wiimotes each for a total of 4 Wiimotes

3. SVOBODA'S ALGORITHM FOR CALIBRATION OF A SYSTEM OF MULTIPLE (>2) CAMERAS

3.1 The Multi-Camera Self-Calibration Technique

Svoboda et al. [9] proposed a method for calibrating multiple cameras together. The minimum number of cameras that can be calibrated together using this method is 3, and there is no upper limit. The only calibration object required is an IR point source. Several IR LEDs can be mounted closely together on a wand to form a uniform IR light source which can be seen by almost all of the cameras in all directions. The calibration can be achieved by moving an IR LED through the work volume. The cameras being calibrated do not have to see all of the points where the data is recorded, i.e., only sufficient overlap among the cameras being calibrated is necessary. This property helps in obtaining more coverage volume per Wiimote in the stereo vision system.

Briefly, Svoboda's algorithm is as follows. Let *m* be the number of cameras to be calibrated together, and *n* be the number of calibration points recorded. Also, let X_j be a calibration point with homogeneous coordinates $[x_j, y_j, z_j, 1]^T$ in the world coordinates, where j = 1,….,n. The pinhole camera model in equation (1) can be written for *m* cameras and *n* calibration points as:

$$\begin{bmatrix} \lambda_1^1 \begin{bmatrix} u_1^1 \\ v_1^1 \\ 1 \end{bmatrix} \cdots\cdots \lambda_n^1 \begin{bmatrix} u_n^1 \\ v_n^1 \\ 1 \end{bmatrix} \\ \cdots\cdots \\ \lambda_1^m \begin{bmatrix} u_1^m \\ v_1^m \\ 1 \end{bmatrix} \cdots\cdots \lambda_n^m \begin{bmatrix} u_n^m \\ v_n^m \\ 1 \end{bmatrix} \end{bmatrix} = \begin{bmatrix} P^1 \\ \vdots \\ P^m \end{bmatrix}_{3mX4} [X_1 \quad \cdots \quad X_n]_{4Xn} \quad (9)$$

where P^i is a 3x4 matrix for camera and contains all 11 camera parameters (5 intrinsic and 6 extrinsic). Thus the calibration here involves finding the camera projection matrices P^i and the scaling factors λ_j^i. In the calibration process, the 2D projection coordinates (u,v) of the image of a 3D marker can be first obtained. Then the wrongly recorded data points (outliers) can be detected using the RANSAC analysis [12]. Then the scaling factors λ_j^i can be determined and the missing points can be estimated by the method described by Martinec and Pajdla [13]. The projective structures can be further optimized using the bundle adjustment [14], and the overall matrix in equation (9) can be further factorized to get matrices P and X [15].

3.2 Evaluation Results

Figure 8 shows our experimental setup with 4 Wiimotes mounted on a CAVE frame for evaluation of Svoboda's calibration technique. Two IR LEDs with a known distance apart were waved through the work volume randomly and their image data was collected. The intrinsic and extrinsic parameters were then determined and used to compute the position of each LED at each calibration point. Points were recorded when the LED was detected by at least three of the four Wiimotes. Then the scaling factor was determined with a sufficient number of observations.

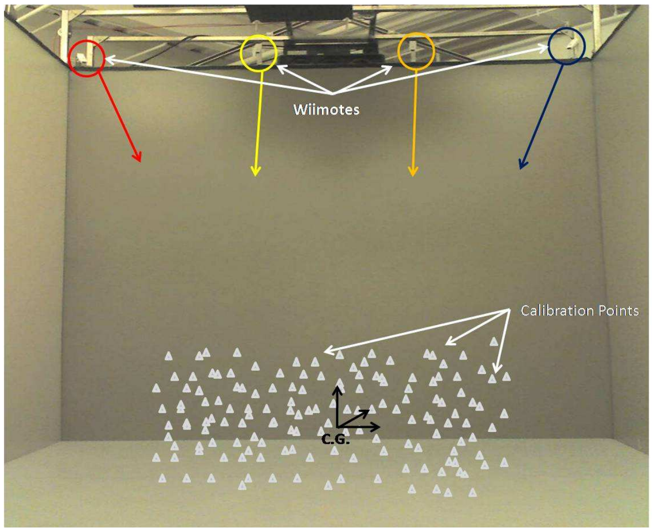

Figure 8. Svoboda's algorithm for self-calibration of 4 Wiimotes

The measurement accuracy is shown in Fig. 9, which shows the difference between the actual distance of the two LEDs and the distance obtained by the motion capture system employing Svoboda's algorithm. As indicated in Fig. 9, the average magnitude of measurement error was 2.37 mm, which is significantly smaller than the 18.9 mm resulted from using the combination of Zhang's and Horn's algorithms shown in Fig. 7.

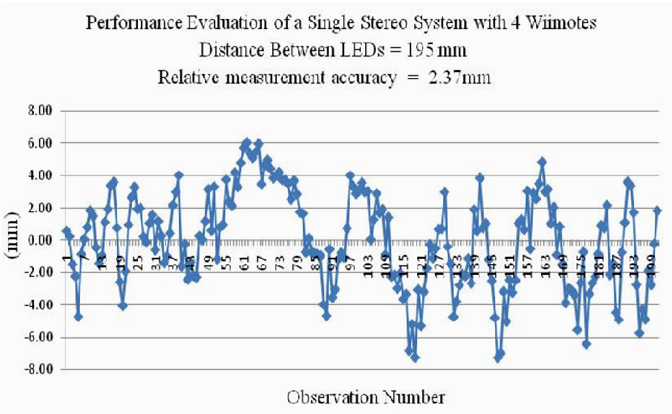

Figure 9. Measurement accuracy for a stereo vision system with 4 Wiimotes using Svoboda's calibration algorithm

4 AN INTEGRATED CAMERA CALIBRATION TECHNIQUE

4.1 Decomposition of Camera Matrix into Matrices of Intrinsic and Extrinsic Parameters

As discussed above, Svoboda's algorithm can be used to obtain intrinsic and extrinsic parameters simultaneously for the cameras in a stereo vision system. This algorithm has been shown in the above experimental evaluation to be more accurate than the combination of Zhang's and Horn's algorithms for a stereo vision system with four Wiimotes. However, our experimental evaluations have also indicated that the values of intrinsic parameters obtained from Svoboda's algorithm deviate more from the known values of the Wiimotes' intrinsic parameters compared with Zhang's algorithm, especially when the overlapping coverage volume between the 4 Wiimotes is becoming small. Thus, the basic idea behind our development of an integrated camera calibration technique is decomposing the camera calibration matrix P^i in equation (9) into a matrix of intrinsic parameters and a matrix of extrinsic parameters, and then using Zhang's algorithm to determine the intrinsic parameters and using Svoboda's algorithm to determine the extrinsic parameters.

It can be shown that the matrix P^i in equation (9) can be decomposed into the separate matrices of intrinsic and extrinsic parameters as follows [15]:

$$P = \begin{bmatrix} A & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \qquad (10)$$

where the two matrices on the right hand side of equation (10) represent the intrinsic parameters and the extrinsic parameters, respectively. Thus, the intrinsic camera parameters can be determined using Zhang's algorithm, and then by using these values of intrinsic parameters in equation (9) the extrinsic parameters of a system of cameras can be determined together using Svoboda's algorithm. To integrate the multiple stereo systems, the relative positions and orientations of the various stereo systems can be determined as discussed in section 2.3

Computer software has been written in C# using Wiimote Library functions to identify dynamically the correspondences between the images for any given marker point. The stereo vision system identifies a set of three or more Wiimotes that detect the marker for any given instance. The obtained image data is then used to solve the extrinsic parameters and then to determine the position of each marker point using equation (9).

4.2 Experiment with a Stereo System with 4 Wiimotes

In this experiment, 4 Wiimotes are calibrated together using the integrated calibration technique described above. A wand with two IR LEDs mounted at a known distance apart is moved randomly in the space. By using the integrated calibration, the positions of the two markers and the distance between them are tracked in real time. The measurement accuracy is shown in Fig. 10, wherein the image data used is the same as that in Fig. 9.

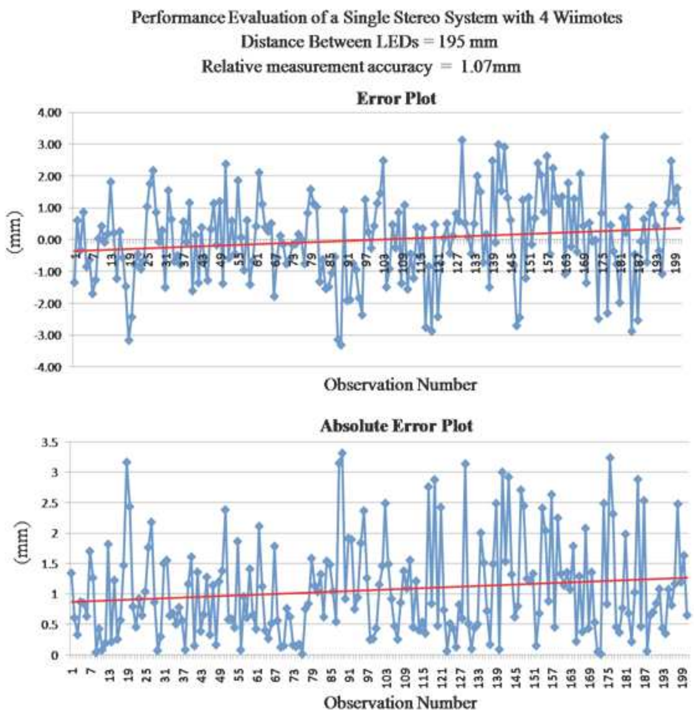

Figure 10. Measurement accuracy for a stereo system with 4 Wiimote using the integrated calibration technique

By determining the intrinsic parameters first for each of the 4 Wiimotes using Zhang's method, the measurement accuracy has improved from 2.37 mm average error (Fig. 9) to 1.07 mm average error. The measurement error is much smaller than the average error of 18.9 mm (Fig. 7) resulted from using the combination of Zhang's and Horn's algorithms.

4.3 Experiment with a Stereo System with 8 Wiimotes

In order to cover a larger measurement volume, the integrated calibration technique is also evaluated for 8 Wiimotes which are arranged such that each set of 4 Wiimotes forms a stereo system and the two systems are integrated into a single stereo system using Horn's algorithm to determine the relative position and orientation of the two systems. Figure 11 shows the 8 Wiimotes mounted in the CAVE, with two stereo subsystems each consisting of four Wiimotes. Figure 12 shows the measurement accuracy for the integrated stereo vision system with 8 Wiimotes. The average magnitude of measurement error is 8.7 mm.

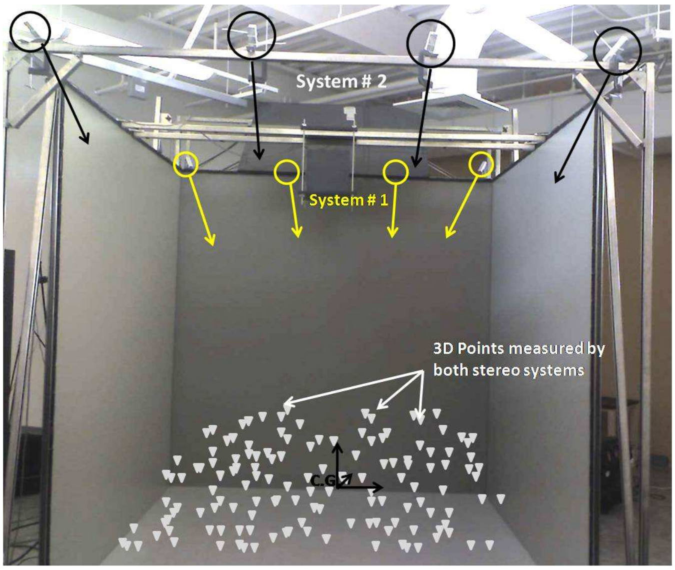

Figure 11. A stereo vision system with 8 Wiimotes

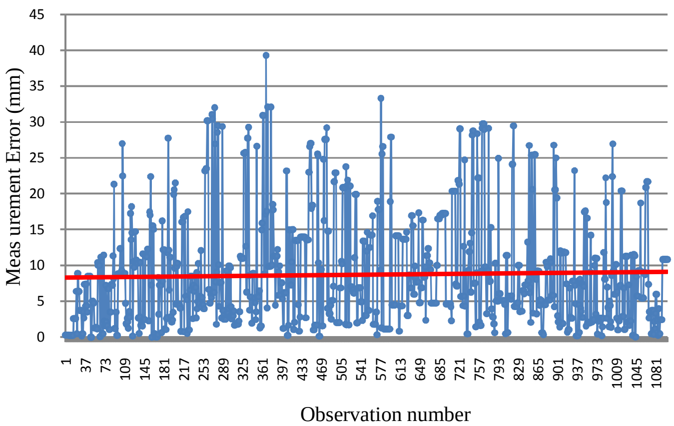

Figure 12. Measurement errors for the stereo system with 8 Wiimotes using the integrated calibration technique

5 CONCLUSIONS

This paper discusses techniques for calibrating multiple digital cameras to form a stereo vision system. The calibration algorithms discussed include Zhang's, Svoboda's, and Horn's algorithms. A new calibration technique has been developed by integrating Zhang's and Svoboda's algorithms. The basic idea of this integrated calibration technique is first using Zhang's algorithm to determine the intrinsic parameters and then using Svoboda's algorithm to determine the extrinsic parameters. This integrated technique can be further used with Horn's algorithm for integration of multiple stereo vision systems into a single stereo system to increase measurement volume. The various techniques are evaluated and compared on measurement accuracy for a stereo vision system setup with 4 Wiimotes. It is shown that the measurement accuracy of the integrated technique has improved over Svoboda's technique and is much better than the measurement accuracy obtained by using the combination of Zhang's and Horn's algorithms. The Wiimote based systems implemented are much cheaper than most of the commercially available motion capture systems, providing great economic benefits for many practical applications. Such a distributed stereo vision system with inexpensive cameras enables the creation of a low-cost, wireless, versatile motion capture system.

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